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Stardust to Planetesimals: A Chondrule Connection?

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Abstract. The unique nature of chondrules has been known for nearly two centuries. Modern techniques of analysis have shown that these millimeter sized silicate objects are among the oldest objects in our solar system. Researchers have devised textural and chemical classification systems for chondrules in an effort to determine their origins. It is agreed that most chondrules were molten at some point in their history, and experimental analogs suggest that the majority of chondrules formed from temperatures $\leq$1600 °C at cooling rates in the range of 100s of degrees per hour.

Although interstellar grains are present in chondrite matrices, their contribution as precursors to chondrule formation is unknown. Models for chondrule formation focus on the pre-planetary solar nebula conditions, although planetary impact models have had proponents.

1. Introduction

Chondrules were first recognized by de Bournon as "curious globules" and reported by Howard (1802) as "small spherical bodies of various sizes" in the Benares chondrite that was seen "to fall from the sky". Howard, together with de Bournon, described the four main components of chondrites: (1) [chondrules] "in great abundance", (2) "pyrites" (troilite), (3) "particles of iron" and (4) "the three are united together by means of a cement..." (matrix). In addition, Howard, with help from de Bournon, performed the first chemical analysis of chondrules: 100 grains were decomposed [by acids] into 50 parts silica, 15 parts magnesia, 34 parts iron, and 2.5 parts nickel, the excess of 1.5% he correctly attributed to the oxidation of iron during decomposition. He compared the Benares stones with three other observed chondrite falls, Wold Cottege (Great Britain), Siena (Italy), and Tabor (Bohemia), and concluded that they were all associated with "meteors" as "stones falling from the atmosphere were repugnant to the mind" and none were connected to volcanic eruptions. Howard's presentation, which included sections by de Bournon, to the Royal Society of London, is one of the most outstanding revelations pertaining to chondrules and meteorites that has ever been made, considering the climate of superstition, bias and the unscientific views of that time. We refer the reader to several excellent historical accounts of early meteorite science: Sears (1975), Sears & Sears (1977), Marvin (1996), and Pillinger & Pillinger (1996).

Our intent in this paper is to non-judgmentally provide the reader with current knowledge on some of the characteristics of chondrules in unequilibrated ordinary chondrites (UOCs), their connections with extrasolar or interstellar dust, and their roles in planetary formation. Most of the issues touched on here are only superficially treated and, thus, we refer the reader to in-depth multidisciplinary summaries on meteorites (Kerridge & Matthews 1988) and chondrules (Hewins, Jones, & Scott 1996). Meteorites, "cosmic " or interplanetary dust particles (IDPs), lunar samples and Mars-source meteorites are the materials that researchers have in hand to use to address first-order questions pertaining to the origin and evolution of the solar system. Information from these samples, together with astronomical observations and theoretical considerations, form our present understanding of the coupling of solid materials from interstellar and early solar nebula sources, through numerous solar nebular and planetary processing events to the end products that we observe today.

Interstellar dust contributions to the early solar nebula are unknown, as most, if not all, of the earliest contributions were thermally processed during large scale nebular events (Boss 1996a). Thus, chondrules probably contain few signatures of any precursor interstellar materials, although they do contain interstellar grains in their matrices (e.g., diamonds, graphite, carbides, organic molecules, Al_2O_3; see Anders & Zinner 1993 and Ott 1994). Moreover, there is a general concensus that interstellar dust infall to the solar system has been a continuous process since before formation of the solar system. Some of this dust that was stored in comets and asteroids early on may have survived impact with Earth (see, for example, Bunch et al. 1996 and Becker, Poreda, & Bada 1996). Inventories of present day interstellar matter are given by Sanford (1996) and Pendleton (1997).

Wood (1984) proposed that chondrule formation occurred when interstellar grains melted during hypervelocity infall into the solar nebula However, the projected composition for these chondrules, or chondrule precursors, appears to be inappropriate (Grossman 1988).

2. General Characteristics

Chondrules are mm-sized round objects consisting mainly of the silicate minerals olivine (a solid solution between Mg_2SiO_4 and Fe_2SiO_4) and pyroxene ($(Mg,Fe,Ca)SiO_3$). The majority of chondrules have textures that indicate that they were molten at some point in their history, while others only show evidence for partial melting.

Approximately 80% of all recovered falls of meteorites to earth are ordinary chondrites (Sears & Dodd 1988). Chondrules occupy approximately 3/4 of the volume of ordinary chondrites (Grossman et al. 1988). This means that over half of the volume percent of meteoritic material reaching earth are chondrules. Although we can't estimate the extent of chondrule formation in the early history of the solar system, it was a widespread and important process. Therefore, chondrules have been the subject of a significant body of research over the past decades, even centuries, and provide us with information about conditions in the solar nebula, and/or parent bodies. Chondrules, along with their "cousins," Ca-Al-rich inclusions, are among the oldest objects available for direct study. At 4.5 billion years old they provide us with a window into conditions in the early solar nebula. Information gained by examining the petrography, mineral chemistry, and isotopes of chondrules can be used to constrain conditions of their formation, and this information can be used to refine models for the formation of primitive meteorites and their parent bodies.

Chondrules are not necessarily pristine, and it is important to identify and separate out secondary effects. The texture and chemistry for the most part reflects the most recent high temperature event experienced by the chondrule, since that event chondrules have been affected by metamorphism and low temperature alteration to varying degrees. The degree of metamorphism of ordinary chondrites is graded on a scale from 3 to 6, with a metamorphic grade of 3 indicating the least metamorphism. As metamorphic grade increases it becomes more difficult to even identify chondrules in the meteorite. Aqueous alteration can also change the mineralogy and composition of the constituent minerals of the chondrule, and can greatly modify the texture. We limit our discussion to chondrules in the least metamorphosed chondrites, generally referred to as unequilibrated ordinary chondrites, or UOCs. In general, UOCs (3.0 to 3.2) have not been affected significantly by aqueous or low temperature alteration.

Fragments and broken chondrules are common in chondrites, and these are generally included in any definition of chondrules. Fragmentation likely occurred during, or shortly before, the parent body accretion process. Ca-Al-rich inclusions (CAIs) are generally not included in the same category as chondrules, although they probably underwent similar processes (e.g., heating and cooling, alteration) during formation. There is also a subset of Al-rich chondrules intermediate in composition between CAIs and the bulk of the chondrule population. Although these Al-rich chondrules are not as common as the more Si-rich variety, their presence could be an important diagnostic clue in any discussion of chondrule formation.

Through our study of chondrules we are attempting to answer specific questions concerning their origin and relationship to other primitive objects. The ultimate origin of chondrule precursor material has not yet been determined. A better understanding of when, where, and how chondrules formed is important to using them to constrain models for the formation of the solar system, or portions thereof. And finally, the accretion of chondrules into parent bodies is an important step in the formation of chondrites.

3. Chondrule Classification

Chondritic meteorites are subdivided into groups based on their average chemistry and oxidation state (see Sears & Dodd 1988 and references therein). Carbonaceous chondrites have the highest refractory element contents, and enstatite chondrites are the most reduced class of the chondrites, with more Fe as metal compared to silicates or sulfides than other chondrites. The ordinary chondrites are subdivided into the H, L, and LL classes based on their Fe/Si ratios, with H chondrites having the highest Fe/Si ratio, and LL the lowest ratio. This is a simplification of the chondrite classification scheme, and chondrite classes can also be deliniated based on other properties.

Chondrules show a wide variation in texture and chemistry, and both characteristics are important clues in deciphering their origin. Therefore, significant efforts have been expended on the classification of chondrules. Classification schemes have been developed based on texture, mineralogy, chemical composition, or a combination of these. The chemical formulas for the most common constituents of chondrules are present in Table 1. Significantly, chondrules do not exist as separate discrete groups under any classification system. In many cases the designation of a specific chondrule to a category can be subjective, and two researchers may place the same chondrule in different groups.

Table 1. Common Minerals in Chondrules

Olivine(Solid Solution)		
	forsterite	Mg_2SiO_4
	fayalite	Fe_2SiO_4
Pyroxene (solid solution)		
	enstatite	$MgSiO_3$
	ferrosilite	$FeSiO_3$
	wollastonite	$CaSiO_3$
	diopside	$CaMgSi_2O_6$
	hedenbergite	$CaFeSi_2O_6$
Pyrrohotite	$Fe_{1-x}S$	
Feldspar		
	albite	$NaAlSi_3O_8$
	anorthite	$CaAl_2Si_2O_8$
	orthoclase	$KAlSi_3O_8$

3.1. Texture/Mineralogy Classification

The most widely used classification scheme for chondrules is based on a combination of texture and mineralogy (Gooding & Keil 1981). Chondrules are subdivided into two major groups based on textural features, porphyritic and non-porphyritic (Table 2). Further subdivisions are based on a combination of mineralogy and texture. Metallic chondrules are a category unto themselves. Barred olivine chondrules are either placed in their own category or included with the non-porphyritic chondrules.

Porphyritic is defined as a texture in which larger crystals are set in a matrix of finer grained or glassy material (Figure 1a, Figure 2b). For chondrules, the larger crystals are most commonly olivine, but may also be pyroxene or a combination of pyroxene and olivine. This leads to the subdivisions for the porphyritic texture (Table 2).

Non-porphyritic chondrules are further subdivided into radial pyroxene, cryptocrystalline, granular olivine/pyroxene, and glassy chondrules. Radial pyroxene chondrules consist of many long narrow pyroxene grains radiating from a

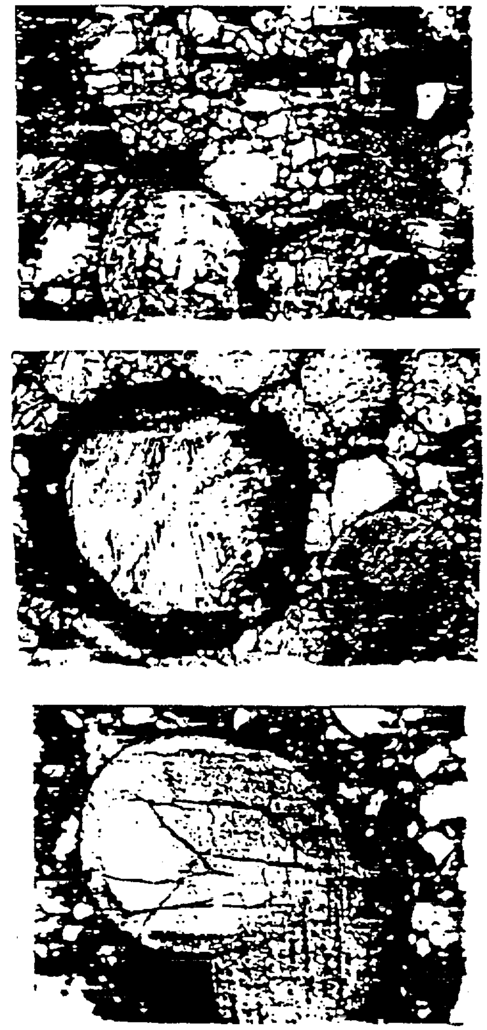

Figure 1. Transmitted light photomicrographs of chondrules from unequilibrated ordinary chondrites. The width of the field of view is approximately 2.51 mm. a) LEW 86505: Note that many chondrules are not spherical, and may be fragments broken during incorporation into the parent body. b) Semarkona: The large chondrules in this photo is surrounded by a well developed accretionary rim, and then surrounded by fine grained matrx-like material. C. Bishunpur: The two large chondrules in this sample appear to have collided while still molten.

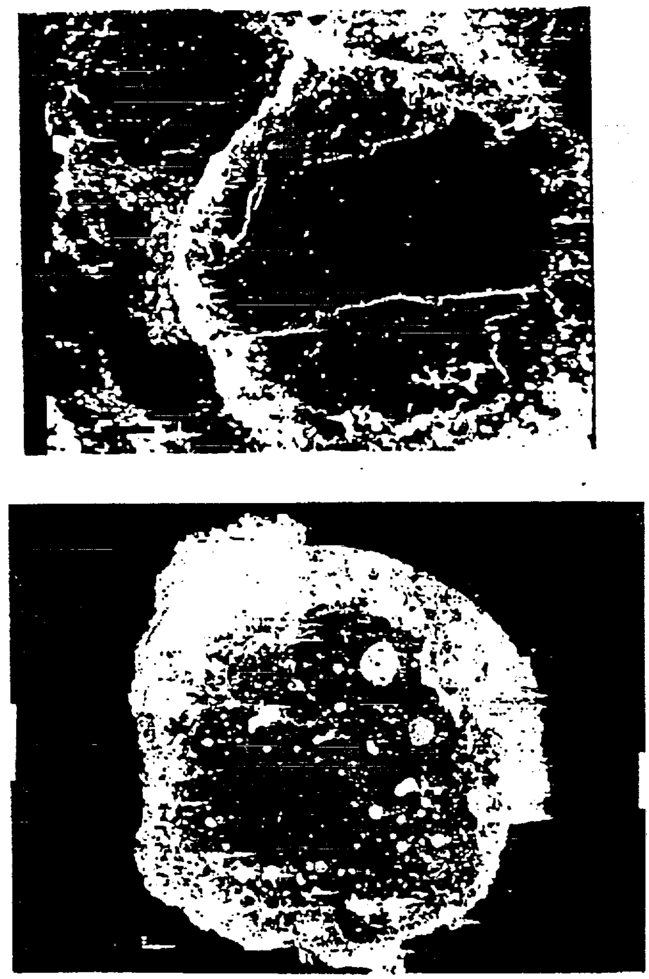

Figure 2. a) A large chondrule with a metal rich rim from the LEW 86505 meteorite. Variation in the mineralogy and chemistry of the chondrule can also be seen by the lighter appearance near the rim. b) A well develped accretionary rim around a chondrule separated from the Allende (CV3) meteorite. The scale bars in the lower left of these backscatter electron photomicrographs are 100 μm long.

Table 2. Texture/mineralogy classification of chondrules[a]

Major Textural Class	Textural Subclass
Porphyritic Chondrules	
	porphyritic olivine
	porhyritic olivine/pyroxene
	poiklitic pyroxene
	granular olivine/pyroxine
Non-Porphyritic Chondrules	
	radial pyroxene
	cryptocrystalline
	glassy
Barred Olivine Chondrules	
Metallic Chondrules	

[a]Gooding and Keil 1981

single nucleation point on the surface of the chondrule. Cryptocrystalline chondrules consist of micron sized pyroxene grains. Some researchers place granular olivine/pyroxene chondrules in the porphyritic category as their texture is similar when imaged in the scanning electron microscope (SEM), although finer-grained than the typical porphyritic chondrule. Glassy chondrules, as their name implies, consist mainly of glass, some are devitrified. Several examples of non-porphyritic chondrules can be seen in Figures 1b and 1c.

Barred olivine chondrules consist of a series of parallel bars of olivine, with a solid olivine rim around the border of the chondrules. Although olivine in the chondrule is part of a single crystal, suggesting that it, like radial pyroxene, crystallized from a single nucleation point.

3.2. Chemical Classification

McSween (1977) extended the textural classification to include the chemical properties of the major minerals in chondrules. Subsequent modifications were made by McSween, Fronabarger, & Driese (1983) and Scott & Taylor (1983). It is important to note that the chemical characteristics of chondrules are not divided into discrete groups, but are a continuum, similar to their textures.

Porphyritic chondrules can be divided into two groups based on the FeO content of the olivine or pyroxene (Figure 3). Type I chondrules are characterized by low FeO, and a negative correlation between FeO and CaO. CaO is an incompatible element in the olivine structure so the amount of CaO present in the olivine is a function of the Ca content of the liquid the olivine crystallized from (higher Ca content of the liquid the higher the content of Ca in olivine) and the speed of crystallization of the olivine (a rapidly growing olivine crystal is less discriminating with respect to what is included in its structure, there is insufficient time to reject Ca). High FeO content in olivine or pyroxene is characteristic of Type II chondrules, olivine is commonly steeply zoned, with rims much higher in iron than the cores of individual crystals; a positive correlation exists between CaO and FeO in these chondrules.

Although Type I chondrules have relatively Mg-rich olivine or pyroxene compared to Type II chondrules, they can still contain a significant quantity of Fe, either as metal or sulfide. The presence of metal and/or sulfides suggests that the conditions of formation were reducing.

Type I and Type II are further subdivided based on the SiO_2 content of the chondrule, with SiO_2- poor chondrules designated as A and SiO_2-rich as B. Since a higher SiO_2 content results in the crystallization of pyroxene rather than olivine, this chemical difference also translates into a mineralogical variation. Therefore, Type IA chondrules consist essentially of FeO-poor olivine. McSween (1977) defined radial pyroxene chondrules as Type III. These chondrules tend to be richer in SiO_2 than the Type I or II porphyritic chondrules.

4. Source Material for Chondrules

The ultimate origin for the material that chondrules formed from is a major unresolved question. Limitations in analytical capabilities keep us from determining whether interstellar material is present in chondrules. The conventional view is that solar nebula condensates with minor contributions from interstellar sources provided precursor materials.

Recycling of these chondrule materials adds an additional complication. If chondrules went through more than one episode of heating and cooling, then the immediate precursor for many chondrules would be an earlier formed chondrule. The presence of relict grains and igneous rims both suggest that chondrules went through more than one heating cycle. Mg-rich forsterite cores of otherwise Fe-rich olivine grains are an example of "relict " material. Olivine grains containing numerous micron-sized Fe metal blebs ("dusty olivine ") are also considered relict if the remainder of the olivine in the chondrule is clear. The presence of Fe metal in a grain implies that formation occurred under more reducing conditions in order to retain some metallic Fe. Jones (1996) estimates that at least 15% of chondrules contain relict material either incorporated into the chondrule while it was molten, or partially melted during the heating cycle. Coarse-grained igneous rims are also evidence of a separate heating event, sufficient to melt the rim precursor, but not the entire chondrule (Podolak et al. 1995; Connolly & Hewins 1991).

5. Constraints on Conditions of Formation

5.1. Experimental Studies

One method of determining constraints on the formation of chondrules is to attempt to duplicate the textures and chemistry of the natural objects in the laboratory.

Chondrule textures have been duplicated under a wide variety of conditions. The following are among conditions of chondrule formation that can be explored in the laboratory: maximum temperature, time at maximum temperature, precursor grain size, cooling rate/cooling profile, and redox conditions.

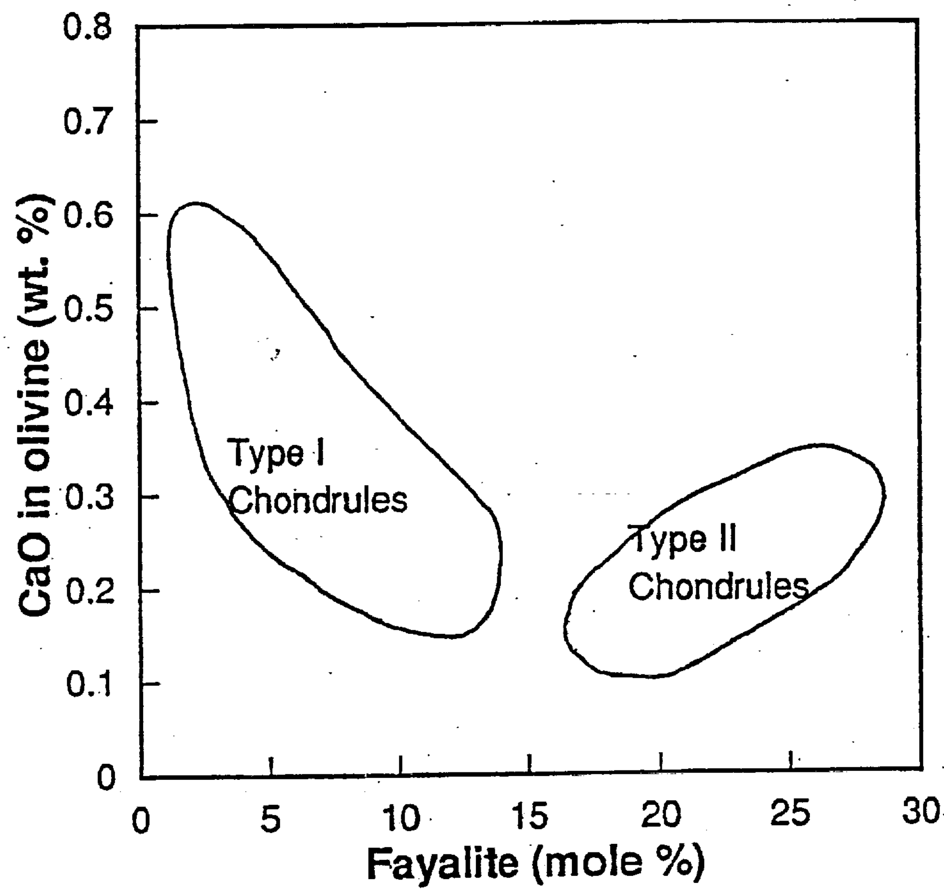

Figure 3. Schematic of the variation in chemistry between Type I and Type II chondrules. The fayalite content of olivine (increasing fayalite indicates increasing FeO content) is negatively correlated with CaO in olivine for Type I chondrules, and positively correlated for Type II chondrules.

Experiments on both CAIs and chondrules have shown that the key factor in determining the texture of a chondrule is the number of nuclei available at the beginning of crystallization (e. g., Lofgren 1983; Stolper & Paque 1986). The number of nuclei can be controlled experimentally (and presumably also in the natural environment) several different ways. As the maximum temperature of the experiment is increased the number of nuclei in the sample decreases. Chondrules with numerous, small grains would have formed under conditions where many nuclei were available, at lower temperatures relative to their liquidus temperature, compared to a radial pyroxene or barred olivine texture, which is indicative of crystallization at or slightly above the liquidus temperature of the chondrule. For a given bulk chondrule bulk composition, as grain size of the crystallized chondrule decreases so does the maximum temperature experienced by the chondrule.

The time a sample is held at its maximum temperature will also affect the number of nuclei present. If a sample is brought to temperature, but held at that temperature for a very short period of time it will retain more nuclei than if it is allowed to remain at that temperature for a longer period of time (Paque 1995). As the sample remains at temperature nuclei are destroyed, up to a point (probably on the order of hours) where the number of nuclei formed is equal to the number of nuclei destroyed (the sample is in equilibrium with respect to the number of nucleation sites). The precursor grain size may have an effect on the nucleation characteristics of the chondrule melt because it would take a longer time at a given temperature to melt larger grains.

By combining the effects of time at maximum temperature with maximum temperature we can hypothesize that a curve exists where the number of nuclei are consistent ("isonuclei") even though we vary the parameters of time and temperature (Figure 4). The conditions necessary to produce a particular chondrule, or CAI, texture may exist over a range of temperature, and other factors are necessary to constrain the conditions of formation.

To complicate the picture even further we can add nuclei to a sample to initiate nucleation. Seeding by puffing fine grained material onto the molten sample before cooling is initiated results in a wide variety of textures, and increases the likelihood of a porphyritic texture (Connolly & Hewins 1995). Since it is likely that fine grained dusty material was floating around in the regime of chondrule production this would increase the proportion of chondrules that would have porphyritic textures. Porphyritic chondrules are the most common texture found, therefore the seeding process may have played a very important role in limiting the number of non-porphyritic chondrules. Otherwise we need to account for a wide range of liquidus temperatures (~200 °C) without a corresponding correlation with texture.

Cooling rate is a more dominant factor for controlling mineral chemistry than the nucleation characteristics discussed above. Cooling rate can significantly affect the chemical zoning in minerals such as pyroxene and olivine that are solid solutions (e. g., Lofgren 1989; Radomsky & Hewins 1990). Variations in chemistry in turn will affect the residual liquid composition as crystallization proceeds and therefore may either enhance or inhibit the crystallization of other minerals.

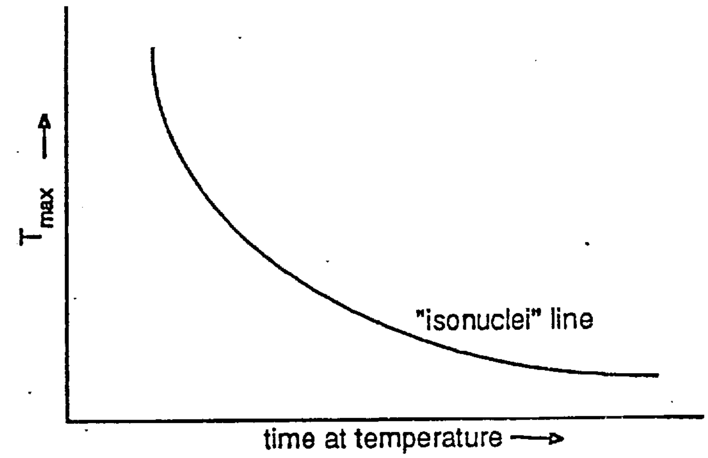

Figure 4. Hypothetical curve which will produce melts with the same quantity of nuclei, and therefore the same texture upon cooling..

Although most experiments are performed under conditions of linear cooling, this is not likely to exist in a natural environment. More likely, a chondrule precursor will be rapidly heated from a base temperature to the maximum temperature and will cool in a non-linear fashion, with a high cooling rate near the maximum temperature and a significantly lower cooling rate as the base temperature is approached (Yu & Hewins 1995). This type of cooling profile is supported by presence of zoning in olivine, which requires a cooling rate high enough (100s of degrees per hour) so that diffusion does not flatten out any zoning profile, combined with TEM observations of anorthite, a late crystallizing mineral in many chondrules, which indicate that they formed under conditions of slow cooling (degree per hour range; Weinbruch & Muller 1994).

In summary, experiments to date indicate that the majority of chondrules formed from temperatures ~1600 °C. The presence of relict grains in some chondrules implies that lower temperatures are likely for most porphyritic chondrules and/or heating rates were very abrupt (e. g., see Podolak et al. 1994). Likely cooling rates for the crystallization of chondrules are in the range of 100s of degrees per hour.

5.2. Chondrule Studies

Additional constraints on the conditions of formation can be obtained from examination of chondrules directly. For example, the presence of relict grains in chondrules places constraints on the temperature of formation and the composition of the source material, as discussed previously.

Physical properties, such as craters in chondrules, compound chondrules, and rims can be used to place constraints on the environment in which chondrules formed and those that were present after formation. Compound chondrules are formed when two chondrules collide while still plastic. Either the density of chondrules was high enough during their formation for collisions to occur or they were produced by parent body collisional processes.

Rims are common on chondrules in ordinary chondrites. A variety of types of rims are found, including "accretionary " rims (small grains sintered onto the chondrule, similar in composition to matrix material; Figure 2b), igneous rims, and rims that consist mostly of metal and/or sulfides (Figure 2a). Chondrules may have formed from continual addition of fine- grained material followed by cycles of heating and cooling. Accretionary rims did not reach temperatures sufficient for melting, while igneous rims were melted, without melting the underlyng chondrule. It is possible that total melting occurred in many cases, homogenizing the original chondrule plus any accreted rim material. Regardless of the heating mechanism, most rims are believed to have formed prior to incorporation into the parent body. Each individual rim has a fairly narrow range in composition, but there is a wide variation among rims in the same meteorite.

6. Environment of Formation

Constraints on the formation of chondrules allow us to begin to examine possible environments for the formation of chondrules. The characteristics of chondrules described above require a rapid ("flash") heating event, followed by cooling that is more rapid than the cooling of the nebula as a whole, yet slower than radiative cooling. The nucleation characteristics of chondrules must have been such that the majority of chondrules formed with a porphyritic texture. This could have been accomplished either through an upper limit on the peak temperatures experienced by the majority of chondrules, or by the addition of nuclei during cooling.

The most popular hypotheses for chondrule formation focus on the preplanetary solar nebula, owing to an apparent need to explain chondrule characteristics by nebular processes. Pro and con issues for most proposed mechanisms are addressed by Lux et al. (1981) and Boss (1996b). Planetary impact origin appeared to have too many problems and was mostly abandoned, although Sears, Huang, & Benoit (1995) have recently challenged arguments against the impact hypothesis (e.g., Taylor, Scott, & Keil 1983; Grossman 1988). At this time none of the proposed mechanisms is convincing and each raise more critical questions than are answered.

The oldest known material in the solar system are CAIs in the Allende carbonaceous chondrite, which are 4.559 ± 0.004 Gyr as determined by the $^{207}Pb/^{206}Pb$ (Pb-Pb) model (Chen & Wasserburg, 1981). The achondrite Ibitira has a Pb-Pb magmatic age of 4.556 ±0.003 Gyr and the most precise crystallization ages for ordinary chondrites are 4.551 ± 0.003 for the LL chondrite St. Severin (Chen & Wasserburg, 1981) and 4.552 ± 0.003 for two L5 chon drites (Manhes, Gopel, & Allegre 1987). Most other measured achondrites and chondrites appear to have formed between 4.56 and 4.53 Gyr. Tilton (1988) pointed out that these less precise ages cannot be placed in a highly restricted time framework because of their analytical uncertainties and the poorly time-constrained theoretical models for planetesimal and planetary formation.

Hutcheon, Huss, & Wasserburg (1994) concluded from their $^{26}Mg^*/^{27}Al$ analysis that the presence of ^{26}Al in CAIs and absence in chondrules (and achondrites) was due to the "late " formation of chondrules that extended over ≈ 6 Myr. Moreover, they surmised that chondrules were produced by a cyclic process that involved mixing, melting and evaporation, and recondensation; the last cycle was extant with respect to the presence of ^{26}Al.

Recently, a magmatic age of 4.56 (no analytical uncertainties given, Jagoutz et al. 1994) or 4.57 ± 0.03 Gyr (Nyquist et al. 1995) was found for the Martian meteorite ALH 84001, which is the oldest age for any planetary rock. The 30 Myr uncertainty covers most of the time frame of CAI, chondrule, and asteroid (achondritic) formations. Models of solar nebula accretion and evolution predict formation of meter size bodies on a time scale of 0.1 Myr and 1 Myr for asteroid size bodies (see, for example, Weidenschilling 1988; Wood & Morfill 1988; Cuzzi, Dobrovolskis, & Champney 1993); no modelled time scale is given for planet size bodies. A few Myr? Ten Myr?

Conventional wisdom holds to the concept that chondrules formed from nebular processes before planets as chondrules, dust, and some CAIs are considered building blocks for accretion. If we assume that the ages given above are correct, without regard to analytical uncertainties, then Mars paradoxically accreted, evolved, and yielded near surface magmatic products before chondrules existed. In this case, either the modeled dynamic time scales for asteroid/planet accretion and maturation are wrong or the late and extended formation of chondrites is not a nebula process but localized in parent body mechanisms. Of course, we can refer to the analytical uncertainties as the way out of this dilemma, except that the magmatically formed achondrite, Ebitira, is also older than measured chondrules. Clearly, high precision radiometric measurements are needed for all critical samples.

7. Accretion of Chondrules Into Parent Bodies

After the individual chondrules were formed there needs to be a mechanism for accumulating a critical mass of the objects in order to form the chondrite parent body. The process that sufficiently concentrated chondrules for accretion also sorted chondrules by size, resulting in a log normal size-frequency distribution that varies in average diameter for individual chondrite classes (Dodd 1976). Cuzzi, Dobrovolskis, & Hogan (1996) propose that size sorting occurred in a turbulent solar nebula, with objects in a preferred size/density range concentrated in between eddies. Accretion must also account for the proximity of CAIs and chondrules in carbonaceous chondrites, even though they are not thought to have formed in at the same time and place in the early solar nebula.

The origin and role of matrix in the formation of chondritic meteorites is not well understood, yet is important in understanding the early nebula. Fayalitic (Fe rich) olivine is a major component of the most primitive chondrite matrix material. Many theories have been proposed for the origin of matrix material, the two most common being that matrix is just nebular condensates, either processed or not, and the second, that matrix consists of comminuted chondrule fragments. All material identified as presolar has been found in matrix material. Matrix is the host for carbonaceous and interstellar materials in UOC chondrites. Clearly, the matrix was not heated to the temperatures experienced by chondrules, or we would not see any of the surviving carbonaceous and volatile materials.

8. Summary

The texture and chemistry of chondrules provides important constraints on their environment of formation, and therefore, on conditions that were present during at least part of the early history of the solar system.

Although primitive in composition, and considered to be the most unfractionated solar system materials, chondrules may have only recorded the last chapter of many melting/crystallization/mixing cycles in a solar nebula setting, or may only provide information of a parent body origin.

Since chondrules and chondrites were first recognized in 1802 thousands of research reports have been written about them. However, the origin of chondrules in terms of how, where, and when remains unresolved. We recommend that a concerted effort be made, possibly by a consortium of multidisciplinary researchers, to constrain critical questions of chondrule formation. We need to include those who study the basic characteristics of chondrules (age, chemistry, petrography, physical characteristics, etc.), experimental petrologists, and theoreticians to model possible scenarios of chondrule formation. It is only with extensive dialog between the disciplines that there is any hope of advancing our knowledge of chondrule formation beyond that of nearly two centuries past.

"The imperfect knowledge we have of the origin and nature of meteors may likewise be considered as an encouragement for inquiring further... " Edward Howard, 1802.

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